Predictive Strain Model for Mechanistic-Empirical Rutting Design of Asphalt Pavements

Gobin Engleng [#], Pabitra Rajbongshi [*]

[#] Research Scholar, *Department of Civil Engineering, National Institute of Technology Silchar, Silchar-788010*

[*] Associate Professor, *Department of Civil Engineering, National Institute of Technology Silchar, Silchar-788010*

Abstract: **- Structural failure in asphalt pavements is happened primarily due to fatigue and rutting. To measure rutting performance, the critical vertical compressive strain (ε_z) at the top of subgrade layer are normally used in the mechanistic-empirical (M-E) pavement design process. However, the computation of ε_z in a 3-D multilayered pavement structure with distributed loading is a complex phenomenon. This paper attempts to present simple predictive strain transfer function for estimation of ε_z, considering 3-D analysis of asphalt pavements. The developed transfer function is validated and found adequate in prediction of ε_z. Degree of accuracy has also been justified statistically. ABAQUS software is used for analysis of pavement structures.**

Keywords: **- Asphalt pavement, strain, rutting.**

I. INTRODUCTION

Mechanistic-Empirical (M-E) design method is being popularly used for structural design of asphalt pavements (AI, 1999; Austroads, 2004; French, 1997; IRC, 2012; Shell, 1978; TRL, 1993; NCHRP, 2004). Traditionally, the mechanistic parameter like critical vertical compressive strain (ε_z) at the top of subgrade layer is correlated with rutting performance in asphalt pavements. However, the accurate estimation of ε_z in pavement structure is a complex task. Primary reasons of such complexities are multilayered and its interaction between the layers, visco-elastic behavior of asphalt material, structural boundary conditions, axle and wheel configurations, environmental factors etc. To avoid these, certain simplifications and approximations are made and the solutions are obtained through numerical analysis. Software such as ABAQUS, ANSYS, KENPAVE, FPAV etc are used by various researchers (Chandra *et al.*, 2008; Das and Pandey, 1999; Hadi and Bodhinayake, 2003; Kuo and Chou, 2004; Helwany *et al.*, 1998; Lacey *et al.*, 2007; Rahman *et al.*, 2011) for pavement analysis. It requires high technical skill, expertise manpower and computing facility as well. However, a designer or a state department may not be comfortable for such infrastructures and efforts. This paper attempts to present simple expressions for strain calculation in multilayered asphalt pavements, including its acceptability and validation. Finite element method (FEM) based software 'ABAQUS' is adopted for analysis of multilayered pavement sections.

II. BACKGROUND

Current practice of asphalt pavements design, popularly known as Mechanistic-Empirical (M-E) design method is followed in various guidelines (AI, 1999; Austroads, 1992; French, 1997; IRC, 2012; Shell, 1978; TRL, 1993; NCHRP, 2004). Fatigue and rutting are considered as two primary modes of structural failures. In general, the failure criteria adopted as 20% of surface cracks area in case of fatigue and 20mm of rut depth in case of rutting failure. The numbers of load repetitions till failure is recorded as pavement life. Rutting life (N_r) of the pavement are empirically correlated with the critical strain parameter of the section. A general form of rutting equations may be expressed as given in Equations (1).

$$N_r = c_1 \times \left(\frac{1}{\varepsilon_z} \right)^{c_2} \qquad (1)$$

where, N_r is the rutting life; ε_z is the initial critical vertical compressive strain at the top of subgrade layer; and, c_1 and c_2 are regression constants. Different literatures suggest different values for these parameters. Some of them are listed in Table 1.

TABLE 1. Parameters of rutting equation used in M-E pavement design.

Organization	c_1	c_2	References
Indian Roads Congress	$4.166\text{x}10^{-8}$	4.534	(IRC, 2012)
Asphalt Institute	$1.36\text{x}10^{-9}$	4.477	(AI, 1999, Huang, 2004)
Shell Research	$6.15\text{x}10^{-7}$	4.0	(Behiry, 2012; Shell, 1978)
US Army Corps of Engineers	$1.81\text{x}10^{-15}$	6.527	(Behiry, 2012; Huang, 2004)
Belgian Road Research Center	$3.05\text{x}10^{-09}$	4.35	(Huang, 2004)
Transport and Road Research Laboratory	$1.13\text{x}10^{-06}$	3.75	(Huang, 2004; TRL, 1993)

It may be mentioned that N_r and ε_z shall be in respect of same loading conditions (say, standard axle load of 80kN). Replacing N_r by the total number of traffic repetitions to be sustained during the design life, the maximum allowable ε_z value can be determined from Equation (1). Accordingly, comparing these strains values with the computed ε_z as obtained from structural analysis, the thicknesses of the design layer(s) can be decided iteratively.

To calculate ε_z value, it needs to solve 3-D equilibrium and compatibility equations, along with adequate boundary conditions. Approximate solution can be obtained through numerical analysis. FEM is one of the most powerful numerical techniques, which is widely used for such solutions. FEM based software 'ABAQUS' has been adopted by various researchers (Hadi and Bodhinayake, 2003; Kuo and Chou, 2004; Helwany *et al.*, 1998; Lacey *et al.*, 2007; Rahman *et al.*, 2011) for numerical analysis of pavement structures. In the present work also, ABAQUS is used to model and analyze the asphalt pavements, and it is discussed in the next section.

III. MODELING OF PAVEMENT STRUCTURE

Normally, an asphalt pavement structure contains 3 to 4 number of load bearing layers. In this study, a 3-layered and a 4-layered pavement has been modeled as 3-D nonlinear elastic structure with finite boundaries. A 3-layered pavement section is shown in Figure 1. FEM based analysis of the pavement is carried out in the ABAQUS environment. Eight noded linear brick elements with reduce integration (C3D8R) is used in analysis, which considers only one integration point at the middle. This element has ability to reduce the computational effort without significant affect on the accuracy. Each element is considered with three degrees of freedom (i.e. displacement in X, Y and Z -directions). Pavement section of 3.5m×10m with end conditions of zero displacement in transverse (-X) and longitudinal (-Y) directions, and fixed end at the bottom of subgrade are used, including rough interface between two layers. A fine mesh of 4.9cm×7.2cm for asphalt layer, and coarse mesh of 9.8cm×14.24cm for granular and subgrade layers are chosen. This is depicted in Figure 1. The analysis of pavement structures has been discussed in the next section.

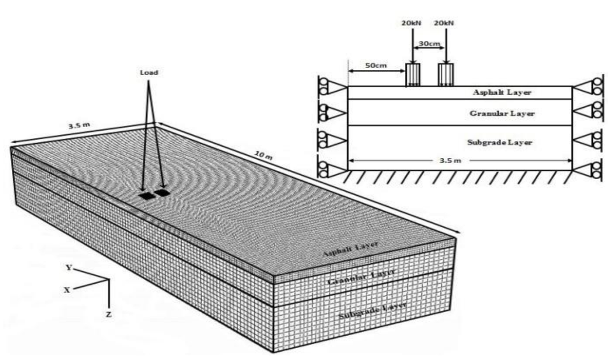

Figure 1. A 3-layered asphalt pavement structure.

IV. PAVEMENT ANALYSIS AND MODELS DEVELOPMENT

In M-E pavement design process, the rutting performance is predicted based on initial critical vertical compressive strain (ε_z) at the top of subgrade. Table 2 shows the layers information for a 3-layered pavement section. To represent the different cases, possible ranges of each parameter has been considered as shown in the table. Poisson's ratio is taken as constant due to negligible effect (Huang, 2004). A uniformly distributed standard dual wheel load of 20kN each with tyre pressure of 0.7MPa over its contact area has been adopted for all the cases.

For different combinations of layers input as given in Table 2, the strain parameter (ε_z) are computed through ABAQUS. Figure 2 shows the strains contour in one case obtained from the ABAQUS analysis. The variations of ε_z with asphalt modulus (E_1) is shown in Figure 3. Negative value indicates compression. Similarly, ε_z variations with other variable parameters are also presented in Figures (4) – (7).

TABLE 2. Layers information used for 3-layered pavement analysis.

Layer	Thickness (cm)	*E*-value (MPa)	Poisson's ratio
Asphalt layer	15 – 20	800 – 2000	0.3
Granular base layer	30 – 50	200 – 400	0.35
Subgrade	100	40 – 100	0.35

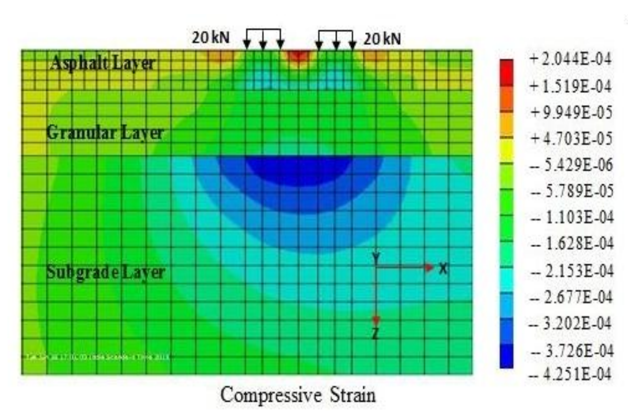

Figure 2. Contour plots of compressive strain in 3-layered pavement structure.

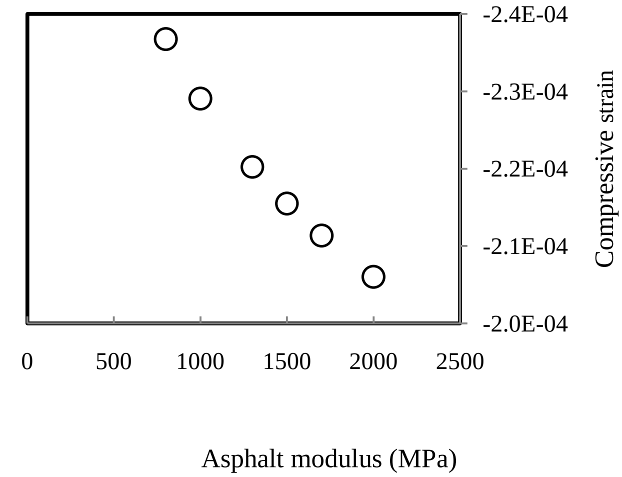

Figure 3. Strain variations with modulus (E_1) of asphalt layer.

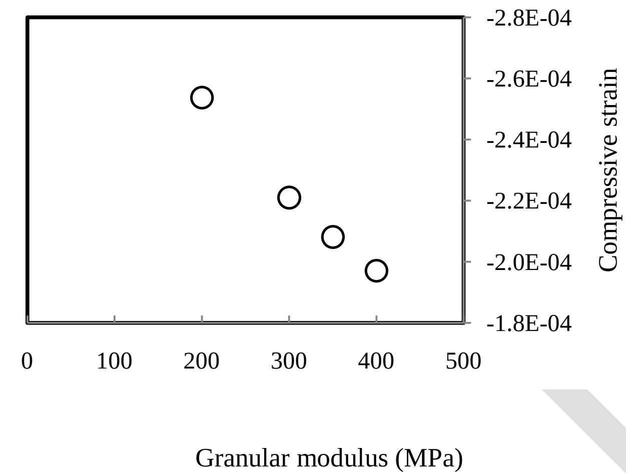

Figure 4. Strain variations with modulus (E_2) of granular layer.

From Figures (3) – (7), it is observed that ε_z parameter is closely correlated with the independent parameters. Combining all the independent variables together, the nonlinear multivariable best fit curves for a 3-layered pavement structure are derived using EViews as given in Equation (2).

$$\varepsilon_z = r_1 + r_2 \ln(E_1) + r_3 \ln(E_2) + r_4 \ln(E_3) + r_5 \ln(h_1) + r_6 \ln(h_2) \qquad (2)$$

where, E_1, E_2 and E_3 are the modulii of asphalt, granular and subgrade layer respectively in MPa; h_1 and h_2 are the thicknesses of asphalt and granular layer respectively in cm; and r_i are the model parameters. The r_i parameters are tabulated in Table 3. From Table 3, it is seen that all the parameters show reasonable contribution to ε_z . This is what it is expected also.

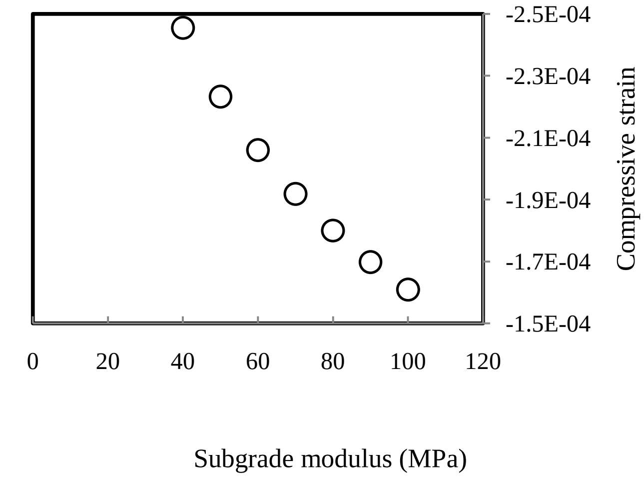

Figure 5. Strain variations with modulus (E_3) of subgrade layer.

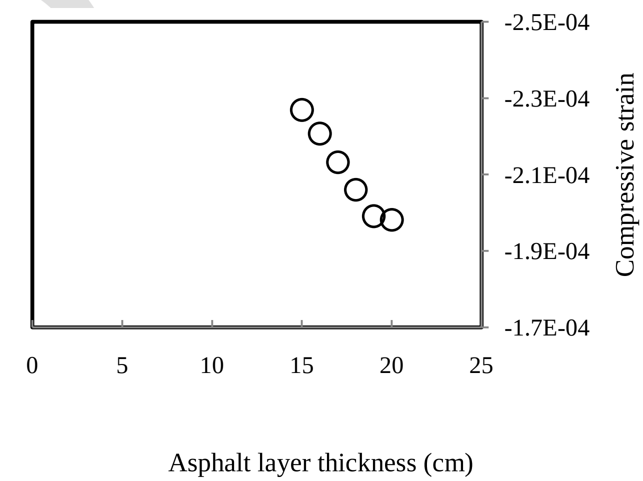

Figure 6. Strain variations with asphalt layer (h_1) thickness.

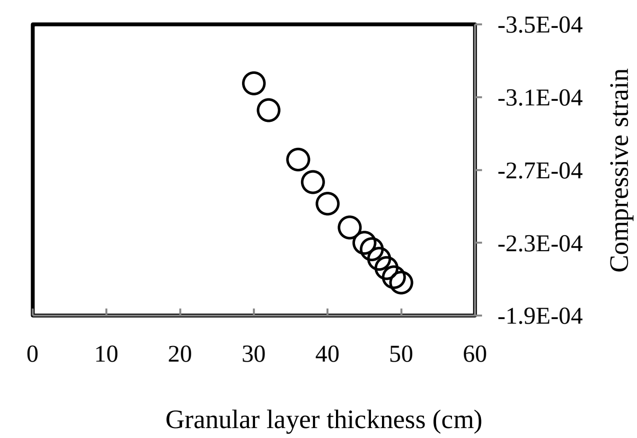

Figure 7. Strain variations with granular layer (h_1) thickness.

TABLE 3. Parameters of strain model for 3-layered pavement structure.

Parameter	Value
r_1	$- 2.441\times10^{-03}$
r_2	$3.20\times x10^{-05}$
r_3	7.299×10^{-05}
r_4	9.529×10^{-05}
r_5	1.07×10^{-04}
r_6	2.236×10^{-04}

Equation (2) is obtained statistically and therefore, it is essential to justify its confidence level in prediction. To this effect and to examine the adequacy of model, various statistical parameters of the strain model are evaluated and are tabulated in Table 4. As seen in the table, it may be concluded that the independent parameter posses good correlation with the dependent parameters (i.e. ε_z) and may be acceptable.

In a similar way, the strain transfer functions are also developed for 4-layered pavement structures viz. asphalt, granular base, granular sub-base and subgrade layers, and found that the strain parameter (ε_z) is closely correlated with the structural input parameters. The nonlinear multivariable best fit curves for ε_z in 4-layered pavement structure is derived as given in Equation (3).

TABLE 4. Statistical parameters of the strain model for 3-layered pavement structure.

Parameter	Compressive strain model
R-squared	0.996
Adjusted R-squared	0.996
Std. error of regression	1.57×10^{-06}
Sum squared residue	7.38×10^{-11}
F-statistic	1740
Prob. of F-statistic	0.000

$$\varepsilon_z = r_1 + r_2 \ln(E_1) + r_3 \ln(E_2) + r_4 \ln(E_3) + r_5 \ln(E_4) + r_6 \ln(h_1) + r_7 \ln(h_2) + r_8 \ln(h_3) \quad (3)$$

where, E_1, E_2, E_3 and E_4 are the modulii of asphalt, granular base, granular sub-base and subgrade layer respectively in MPa; h_1, h_2 and h_3 are the thicknesses of asphalt, granular base and granular sub-base layer respectively in cm; and r_i are the model parameters. The r_i parameters are tabulated in Table 5. To examine the adequacy in strain predictions, various statistical parameters of the strain models are evaluated using EViews and are tabulated in Table 6. As seen in the table, it may be concluded that the independent parameter posses good correlation with the dependent parameters (i.e. ε_z) and thus, the correlation may be acceptable.

TABLE 5. Parameters of strain model for 4-layered in pavement structure.

Parameter	Value
r_1	$- 2.440\times10^{-03}$
r_2	2.85×10^{-05}
r_3	4.44×10^{-05}
r_4	3.83×10^{-05}
r_5	1.11×10^{-04}
r_6	9.94×10^{-05}
r_7	1.11×10^{-04}
r_8	1.37×10^{-04}

TABLE 6. Statistical parameters of the strain model for 4-layered pavement structure.

Parameter	Compressive strain model
R-squared	0.999
Adjusted R-squared	0.999
Std. error of regression	5.78×10^{-07}
Sum squared residue	1.10×10^{-11}
F-statistic	5466
Prob. of F-statistic	0.000

Further, it is attempted to validate the developed models using separate sets of input data, through ABAQUS and KENPAVE analysis as well. This is illustrated in the next section.

V. VALIDATION

In order to validate the statistical strains transfer functions, different asphalt pavement sections are analyzed considering separate sets of input data. The strain (ε_z) values are evaluated using both ABAQUS and KENPAVE analysis program. The comparison of ε_z values calculated from pavement analysis and the developed strain models are shown in Figure 8. To compare the strain transfer function in terms of the rutting life (N_r) prediction, a comparison of N_r values in million standard axles (msa) are presented in Figure 9. Regression constants of the rutting equations are adopted as per TRL models (Huang, 2004). Thus, from Figure 8 or Figure 9 it may be concluded that the model predictions are sufficiently good as that of ABAQUS or KENPAVE analysis programs.

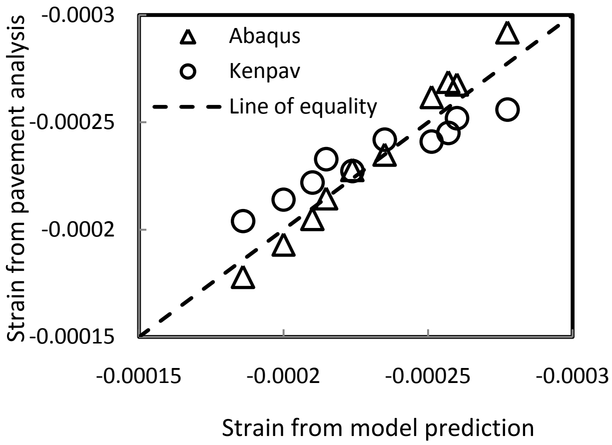

Figure 8. Comparisons of compressive strain of pavements.

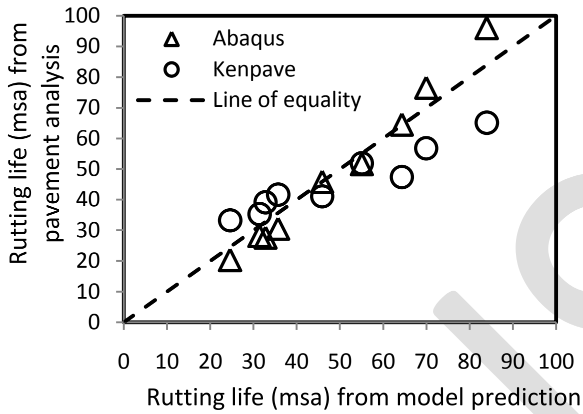

Figure 9. Comparisons of rutting life of pavements.

VI. CONCLUSIONS

Simple strain transfer functions for vertical compressive strain (ε_z) in asphalt pavement is developed for 3 layered and 4-layered pavement structures and presented in the paper. The proposed ε_z functions are validated and found adequate in prediction. Statistically also, these transfer functions are tested and found confident. Thus, the proposed strain models can easily be adopted for rutting life estimation in the pavement design process, and can be avoided complex analysis and high computational effort. Also, to incorporate the reliability or probability in pavement design, one can easily know the distribution of ε_z for any given distributions of their input parameters. For example, the ε_z parameter would follow normal distribution, in case the inputs E_i and h_i in strain functions (Equations (2)-(3)) are log-normally distributed.

Towards M-E design of asphalt pavements, this work focuses on establishing an acceptable statistical correlation between the strain parameter (ε_z) and layers information in 3-layered and 4-layered pavement structures. However, they have few limitations like the effect of moving loads, visco-elastic behavior etc are not accounted and are recommended for further studies.

REFERENCES

[1]. Asphalt Institute (AI). (1999). *Thickness design - asphalt pavements for highways and streets*, Manual Series No.1, 9th Edition, The Asphalt Institute, Lexington, Ky, USA.

[2]. Austroads. (2004). *Pavement design*, Austroads, Sydney, Australia.

[3]. Behiry, A.E.A.M. (2012). “Fatigue and rutting lives in flexible pavement”, *Ain Shams Engineering Journal*, Ain Shams University, Vol.3, pp.367–374.

[4]. Chandra, S., Viladkar, M.N., and Nagrale, P.P. (2008), “Mechanistic approach for fiber-reinforced flexible pavements”, *Jr. of Transportation Engineering*, ASCE, 134(1), pp.15-23. DOI: 10.1061/(ASCE)0733-947X(2008)134:1(15).

[5]. Das, A., and Pandey, B.B. (1999). “Mechanistic-empirical design of bituminous roads: an Indian perspective”, *Jr. of Transportation Engineering*, ASCE, 125(5), pp.463-471. DOI: 10.1061/(ASCE)0733-947X(1999)125:5(463).

[6]. French. (1997). *French design manual for pavements structures*, Guide Technique, LCPC and SETRA, Francaise.

[7]. Hadi, M.N.S., and Bodhinayake, B.C. (2003). “Non-linear finite element analysis of flexible pavements”, *Advances in Engineering Software* , Elsevier, Vol.34, pp.657-662. DOI: 10.1016/S0965-9978(03)00109-1.

[8]. Helwany, S., Dyer, J., and Leidy, J. (1998). “Finite-element analyses of flexible pavements”, *Journal of Transportation Engineering*, ASCE, 124(5), pp.491–499. DOI: 10.1061/(ASCE)0733-947X(1998)124:5(491).

[9]. Huang, Y.H. (2004). *Pavement analysis and design*, Second Edition, Pearson Prentice Hall, New Jersey.

[10]. Indian Roads Congress (IRC). (2012). *Guidelines for the design of flexible pavements*, IRC: 37-2012, 3rd Revision, The Indian Roads Congress, New Delhi, India.

[11]. Kuo, C.M., and Chou, F.J. (2004). “Development of 3-D finite element model for flexible pavements, *Journal of the Chinese Institute of Engineers*, 27(5), pp.707-717. DOI: 10.1080/02533839.2004.9670918.

[12]. Lacey, G., Thenoux, G., and Rodríguez-Roa, F. (2007), “Three-dimensional finite element model for flexible pavement analysis based on field modulus measurements”, *The Arabian Journal for Science and Engineering*, Vol. 33, No. 1B, pp.65.

[13]. National Cooperative Highway Research Program (NCHRP). (2004). *Mechanistic-empirical design of new & rehabilitated pavement structures*, NCHRP Project 1-37A, Transportation Research Board, Washington, D.C.

[14]. Rahman, M.T., Mahmud, K., and Ahsan, S. (2011). "Stress-Strain characteristics of flexible pavement using Finite Element Analysis", *International Journal of Civil and Structural Engineering*, 2(1), pp.233-240.

[15]. Shell. (1978). *Shell pavement design manual – asphalt pavement and overlays for road traffic*, Shell International Petroleum Company Limited, London, UK.

[16]. Transport Research Laboratory (TRL). (1993). *A guide to the structural design of bitumen-surfaced roads in tropical and sub-tropical countries*. Overseas Road Note 31, 4th Edition, Overseas Center, TRL, London.